47

Research Report

Alternate Wet/Dry Irrigation in Rice Cultivation: A Practical Way to Save Water and Control Malaria and Japanese Encephalitis?

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IWMI

International Water Management Institute

Research Reports

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Contents

Acronyms *iv*

Summary *v*

Introduction *1*

Water Saving and Productivity *2*

Vector Control *8*

Other Aspects of AWDI *18*

Subjects for Further Studies *20*

Conclusions *22*

Glossary *25*

Literature Cited *26*

Acronyms

AWDI	Alternate wet/dry irrigation
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
ICIPE	International Center of Insect Physiology and Ecology
IPM	Integrated pest management
IRRI	International Rice Research Institute
IWMI	International Water Management Institute
JE	Japanese encephalitis
PEEM	Panel of Experts on Environmental Management for Vector Control
UNCHS	United Nations Center for Human Settlements
UNEP	United Nations Environment Program
WHO	World Health Organization

Summary

Due to increasing scarcity of freshwater resources that are available for irrigated agriculture, in the future, it will be necessary to produce more food with less water. More irrigated land is devoted to rice than to any other crop. One method to save water in irrigated rice cultivation is the intermittent drying of the rice fields instead of keeping them continuously flooded. This method is referred to as alternate wet/dry irrigation (AWDI). Apart from the water saving potential of AWDI there are also potential human health benefits. Rice fields provide a habitat for mosquitoes to lay their eggs, and rice agrosystems have traditionally been associated with mosquito-borne diseases, especially malaria and Japanese encephalitis.
If rice fields are dried, as in AWDI, the mosquito larvae will die and less adult mosquitoes will be produced in the rice fields. This could lead to a lower incidence of malaria and Japanese encephalitis. In certain areas and under the right conditions, AWDI is a promising method in irrigated rice cultivation with dual benefits of water saving and human disease control, while maintaining rice yields at least at the same level. However, many factors play a role in determining the success or failure of AWDI. Some of these factors can be influenced, such as irrigation infrastructure and irrigation management capacity, while others cannot be, such as rainfall and soil conditions. The increased productivity of water, not the mosquito control is likely to be the critical factor that will make farmers and irrigation department officials adopt AWDI in water-scarce areas. This report reviews previous studies on AWDI with a focus on mosquito vector control, water saving, and rice yields. Examples are given from a number of countries and recommendations are provided for further studies.

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Introduction

For nearly half of the world's population (2.7 billion people), rice is the staple food providing 35–60 percent of the calories consumed (Guerra et al. 1998). More than 75 percent of the world's rice is produced in irrigated rice lands, which are predominantly found in Asia. The abundant water environment in which rice grows best differentiates it from all other important crops. But water is becoming increasingly scarce. By 2025, the per capita available water resources in Asia are expected to decline by 15–54 percent compared with 1990 (Guerra et al. 1998). Agriculture's share of water will decline at an even faster rate because of the increasing competition for available water from urban and industrial sectors. Because these urban and industrial demands are likely to receive priority over irrigation, it becomes essential to develop and adopt strategies and practices that will use water efficiently in irrigation schemes, particularly in parts of Africa, where demand for rice is increasing and water is less abundant than in Asia. One such strategy and practice that is said to use water efficiently in irrigation schemes is the alternate wet/dry irrigation method (AWDI) of cultivating rice, which is increasingly used in parts of Asia, especially in Japan, China, and India. AWDI implies that rice fields are not kept continuously submerged but are allowed to dry intermittently during the rice growing stage.

Producing more rice with less water from irrigated systems could provide opportunities to improve human health. Rice cultivation has traditionally been associated with vector-borne diseases, especially malaria and Japanese encephalitis (Service 1989a; Lacey and Lacey 1990). The mosquito vectors of these diseases lay eggs in standing water and the larvae need about 7–10 days in a water environment to develop into adult mosquitoes. The intermittent drying of rice fields was therefore tested for its mosquito control potential as far back as early twentieth century. Some dramatic results were obtained in studies in Portugal (Hill and Cambournac 1941) and Indonesia (reviewed in Takken et al. 1990). With the introduction of DDT after World War II, water management and other environmental measures to control mosquitoes were neglected. It is only since the 1980s, after the failure of the DDT-based eradication campaigns of malaria that environmental control measures are receiving renewed attention (World Health Organization 1982, 1983; Ault 1994).

There is a great need to increase the productivity of water in rice irrigation systems in a sustainable way. Any agricultural or water management technique that can achieve this objective and also has health benefits must be viewed as an important contribution to sustainable development as it enables people to remain fit and spend more time on their land attending to their crops. The WHO/FAO/ UNEP/UNCHS Panel of Experts on Environmental Management for Vector Control (PEEM) has repeatedly suggested research on rice ecosystem management for human disease-vector control to international agricultural research centers. At an international workshop on 'Health and Irrigation' in Copenhagen in 1997, AWDI for vector control was discussed as a potential field of research for the International Water Management Institute (IWMI) (Birley 1998). The present review of AWDI was done to provide a baseline for a number of case studies that are now being implemented in India, Sri Lanka, China, and Kenya. The specific question addressed in this report is whether AWDI is a potential method to save water and whether it can contribute to the control of vector-borne diseases. Such dual benefits could be an important reason to recommend AWDI in rice cultivation. As studies have been done in different countries and by different sectors, it was felt necessary to review past work in a comprehensive way bringing together results from agricultural, irrigation, and bio-medical research. Other important aspects of AWDI such as the effect on agrochemical use, and the necessary institutional arrangements are only briefly considered. The main outcomes of existing studies are discussed and areas for further research and prospects for implementation are identified.

Water Saving and Productivity

From time immemorial, rice has been grown in lowland areas under flooded conditions. Rice grown under traditional practices in the Asian tropics and subtropics requires between 700 and 1,500 mm of water for a cropping season depending on soil texture (Bhuiyan 1992). The water requirement consists of: (1) 150–250 mm for land preparation; (2) about 50 mm for growing rice seedlings in the nursery before transplanting; and (3) 500–1,200 mm (5–12 mm per day for 100 days) to meet the evapotranspiration (ET) demand and unavoidable seepage and percolation in maintaining a saturated root zone during the crop growth period (Guerra et al. 1998). The actual amount of water used by farmers for land preparation and during the crop growth period is much higher than the actual field requirement. Paddy farmers often store water in their fields as a back-up safety measure against unreliability in water supply. Also, there is often field-to-field irrigation. This leads to a high amount of surface runoff, seepage and percolation accounting for about 50–80 percent of the total water input to the field (Sharma 1989). AWDI is one method that can increase the productivity of water at the field level by reducing seepage and percolation during the crop-growth period. There are different forms of AWDI practiced in different parts of the world. A brief review of such practices and their impact on water saving and productivity is provided in this chapter.

Numerous studies conducted on the manipulation of depth and interval of irrigation to save water use have demonstrated that continuous submergence is not essential for obtaining high rice yields (Guerra et al. 1998). Hatta (1967), Tabbal et al. (1992), and Singh et al. (1996) reported that maintaining a very thin water layer, at saturated soil condition, or alternate wetting and drying can reduce water applied to the field by about 40–70 percent compared with the traditional practice of continuous shallow submergence, without a significant yield loss. In general, the lighter the texture of the soil, the greater the possible reduction in water requirements. The duration of the dry period after the disappearance of ponded water depends on the depth of the groundwater table. The shallower the groundwater table, the longer the interval between irrigation events can be (Mishra et al. 1990, 1997).

Water saving as discussed in this report refers to water saved locally in paddy fields. Whether the water saved locally will result in water savings at the level of the irrigation system or river basin depends on what happens to the drainage water, i.e., the amount of water that is delivered to the field but not used by the crop for ET. Drainage water may flow to saline areas or to the oceans, where the water is effectively lost to further beneficial uses. In this case, reducing drainage can result in real water savings. On the other hand, in paddy irrigation systems, drainage water flows from field to field and recycling occurs. Because of recycling and reuse, one person's drainage may be another person's water supply (Seckler 1996). In this case, reducing drainage from rice fields is not a real water saving. So, the quantum of water saved through AWDI depends on the location of the paddy field and what happens to the drainage water. The concepts of water conservation and water productivity and its relation to AWDI are presented in Box 1.

BOX 1.
The concepts of water conservation and water productivity.

Two sets of terminologies have to be used to describe water conservation and water productivity. The water use efficiency index measures water conservation and is defined as productivity (P) per unit of water supplied. The water supply includes both diverted water plus rainfall. Water productivity is defined as productivity per unit of water consumed. Water consumed is essentially evapotranspiration, which includes evaporation from soil and transpiration through plants. The water use efficiency index is related to water productivity by the following equation.

$$\left(\frac{P}{S\ \textit{Water supplied}}\right) = \left(\frac{P}{S\ \textit{Water consumed}}\right) x \left(\frac{S\ \textit{Water consumed}}{S\ \textit{Water holding capacity}}\right) x \left(\frac{S\ \textit{Water holding capacity}}{S\ \textit{Water supplied}}\right)$$

Or in other words, water use efficiency index = water productivity x water uptake factor x water management factor.

The water use efficiency index can be increased by three factors as indicated above. The first factor is water productivity. It can be increased by increasing P or reducing water consumed, or by both. Manipulation of this term is in the realm of plant scientists and bio-technologists. The second factor is the water uptake factor, which is in the realm of soil scientists. Given a particular type of plant, the issue is how to manipulate the soil and its structure so that it can hold sufficient water and supply adequate water so that productivity can be increased. The third is the water management factor wherein the manager operates the system in such a way that he is able to supply water just sufficient to accommodate within the root zone and meet the crop water requirement in a timely fashion. AWDI is one method of managing the water so that water will not be wasted but it will aid the root growth, facilitate higher nutrient uptake, and increase land and water productivity.

On-Farm Studies by IRRI in the Philippines

The International Rice Research Institute (IRRI) conducted a series of on-farm (field level) experiments between 1968 and 1972 to establish the relationship between the quantity of water applied and the rice yield. The hypothesis was that as the level of water applied diminishes, yields would drop very sharply, reflecting the extreme sensitivity of puddled rice to drought conditions. It was predicted that the general nature of the response would take the shape of a sigmoid or logistic curve.

During the 1968 dry season, all experimental plots were kept flooded to a depth of 5 centimeters until panicle initiation (60 days after transplanting). Then water was applied at five-day intervals at five levels ranging from an average of 2 mm/day–6 mm/day. The soil moisture content never fell below 50 percent of approximate field capacity. At the lower water application levels, yields were reduced only slightly, in comparison with flood-controlled fields.

In 1969, seven treatments consisting of 2–8 mm average daily application applied at five-day intervals plus two flooded controls were used. The treatments were started shortly after transplanting (as compared with panicle initiation in 1968). The results indicated that yield was greatest at 8 mm per day. Maximum yield per millimeter of supplied water was achieved at 7 mm/day. Below a water application level of 6 mm/day, yields dropped sharply and were almost zero at 4 mm/day. At 8 mm/day, the plot was maintained from a flooded to saturated level. At 7 mm/day, intermittent flooding to saturation was maintained before flowering. From flowering to maturity, the plot fell below saturation. At water application levels below 7 mm/day, all plots fell below saturation before flowering. The plants in the plot receiving 3 mm/day flowered but produced no grain; plants in the plot receiving 2 mm/day did not flower.

In 1972, IRRI analyzed the effect of environmental factors on the functional yield-stress relationships based on data from 1969, 1970, and 1971 dry seasons. The results indicated that for a given season, low yields are closely associated with the duration of time during crop growth that soil moisture is seriously depleted. The 1969 dry season had more solar radiation during the last 45 days before harvest and less rainfall than the dry seasons in 1970 and 1971. The high solar radiation increased yields under ample water treatments to levels higher than in 1970 or 1971. But under low levels of water application the high solar radiation in combination with low rainfall appeared to have depressed yields by accelerating the decline of soil moisture. Thus, high solar radiation appears to be associated with high yields only where water is not a limiting resource. Under these conditions, plant ET can increase in response to high levels of solar energy. But with an insufficient supply of water, high solar energy causes greater moisture stress in the plants. For areas receiving limited water, therefore, higher yields can be expected in years when solar energy is lower, cloudy days are more frequent, and rainfall is greater.

Bhuiyan and Tuong (1995) conducted research over several years and concluded that a standing depth of water throughout the season is not needed for high rice yields. About 40–45 percent of the water normally used in irrigating the rice crop in the dry season was saved by applying water in small quantities only to keep the soil saturated throughout the growing season, without sacrificing rice yields. However, in some years, this method of water management caused more weed problems. Weeds could be controlled by using appropriate herbicides or by maintaining a shallow standing water depth for the first 35–40 days after crop establishment when crop canopies completely shade the land and then maintaining the saturated soil regime until maturity. In this case, the water saving was 25–35 percent. Bhuiyan and Tuong (1995) also noted that farmers were reluctant to adopt water saving because it required more labor and water was cheaply available to them.

North American Studies

Studies conducted in Texas, Missouri, Louisiana, and Arkansas concluded that rice could be produced under non-flooded conditions using furrow and sprinkler irrigation, but that it is not economically viable under conditions in the southern United States (G. Davids 1998, unpublished report). Reduced yields were an important factor in this outcome. Typically, as water supplies became restricted or more costly, it was more economical to switch to alternative crops than to grow rice under non-flooded conditions. This was especially true where capital-intensive irrigation systems such as sprinklers were used. Some of the salient findings of this research were:

- Rice yields under non-flooded conditions generally decreased proportionally with reduced water application (increased stress). There were periods during the rice growth cycle when the yield was particularly sensitive to moisture stress.

- The average yield for sprinkler-irrigated rice was 20 percent less than yields of flooded rice on similar soils, but the specific causes of yield reduction were not fully apparent. The best performing (highest yielding) cultivars had yield reduction of 10–15 percent compared to flooded rice.

- The most drought-resistant rice cultivars produced the same yield under sprinkler irrigation, as under flooded conditions; however, those tend to be low-yielding varieties.

- There was a significant difference among cultivars with respect to drought tolerance.

- Irrigation water requirement for non-flooded rice was 20–50 percent less than for flooded rice, with the difference being strongly dependent on soil type, rainfall, and water management practices.

- Under non-flooded conditions, the ability to apply light, frequent irrigation (every 2–4 days) was needed to avoid stress and efficiently utilize rainfall.

Japanese Studies

Midseason drying of rice fields has been recognized in Japan as a method to obtain higher yields for at least the last 300 years (Mogi 1988). In the late 1950s, AWDI was promoted among farmers and has become a common practice. However, AWDI only starts about one month after transplanting, till then the rice fields are flooded. The changes brought out by different ponding water depths under different water regimes such as continuous ponding, intermittent ponding, and variable ponding and also under different doses of fertilizer application on rice crop production was investigated by Anbumozhi et al. (1998) using controlled experimentation. In intermittent ponding, submergence was maintained until the panicle initiation stage followed by AWDI at an interval of every three days after the disappearance of ponding water. This investigation showed that:

- At 9 centimeters ponding depth, a grain yield of 5.21 t/ha and 4.95 t/ha was obtained with continuous and intermittent ponding, respectively.

- At 9 centimeters ponding depth, AWDI accounted for increased water productivity (1.26 kg/m^3) compared to continuous flooding (0.96 kg/m^3).

- Even though maximum yield per unit of water supplied always occurred with the no-ponding condition, the land productivity measured as grain production per unit of land was 62 percent less than with an optimum ponding water depth of 8 centimeters.

These observations demonstrated that considerable water savings are possible by maintaining an optimum ponding water depth under water-scarce conditions.

Chinese Studies

In the southern part of China, over 70 percent of the cultivated area comes under rice. Under the traditional method, termed "shallow flooding irrigation," the fields are covered with a shallow water layer during most of the rice-growing season. Since the 1980s, in some provinces in South China, a new irrigation technique for rice, termed "water saving irrigation," has been promoted (Mao Zhi 1996). The basic feature of this new irrigation technique is that there is no water layer above the soil surface in rice fields during the growing season from the time the seedlings have recovered. This reduces the percolation, seepage, and runoff from the field. It is claimed that this technique not only saves water but also increases the rice yields. In the experimental fields of the Guangxi Autonomous Region, percolation under water saving irrigation was 67 percent lower than under flood irrigation (table 1).

Under flood irrigation, the groundwater table in rice fields rises up to the soil surface and keeps this level during the period of submersion, and it can be lowered to 0.3–0.8 m below the soil surface during the period of no submersion under water saving irrigation. The soil oxygen content in rice fields under water saving irrigation is 120–200 percent of that under flooding irrigation (Mao Zhi 1993).

According to statistical figures from Yulin Prefecture in the Guangxi Autonomous Region, where water saving irrigation for rice has been adopted in 30,000 hectares, about 100 million m^3 per year of irrigation water for rice has been saved (Mao Zhi 1996). However, at this larger scale it is difficult to estimate the contribution of AWDI to the water savings because different changes took place at the same time. Most important was the introduction of volumetric charges for irrigation water in China, which was a major incentive to use less water. Measures were taken to reduce the conveyance losses of water in canal systems by lining sections of canals that had heavy seepage losses. The loss of water in the fields and in field channels was reduced through AWDI and construction of field irrigation ditches. The ratio of water irrigated to the field to water diverted from the headwork for irrigation ranged from 0.43–0.53 before, and 0.57–0.63 after the introduction of volumetric charging of water. Additionally, the irrigation application efficiency increased because of these measures, so that the gross irrigation quota decreased remarkably. Combined with an increase of rice yield this resulted in high water productivity.

In the Zhanghe Irrigation System in Hubei Province, the AWDI method alternately consisted

TABLE 1.
Mean values of evapotranspiration, percolation, and water requirement over a whole growing season at the Guilin Experimental Station, Guangxi Autonomous Region 1990–92 (measured as mm of water).

Irrigation technique	Evapotranspiration (mm)	Percolation (mm)	Water requirement (mm)
Flood irrigation	765.4	514.9	1280.3
Water saving irrigation	688.8	169.3	858.1

Source: Mao Zhi 1996.

of a shallow water layer, and damp and dry situation of soil on the rice fields at different growing stages of the rice. The water regimes on rice fields for this method are shown in table 2.

TABLE 2.
Water regime adopted in the Zhanghe Irrigation System, Hubei Province.

Growing stages	Depth of water layer (mm) or soil moisture content (%)
Transplanting rice shoots	10–20 mm
Revival of green	0.30 mm
Early and middle stages of tillering	80
Late stage of tillering	Drained, dry field for 5–7 days
Booting and flowering	80
Milk ripening	70
Yellow ripe	Drained, dry field

Source: Mao Zhi and Li Yuanhua (1998).

Based on experimental fields and the practices on the larger area, the net irrigation water saved was 20–35 percent, from 4,080–5,780 to 3,100–4,500 m^3/ha/year. The rice yield increased by 15–28 percent after the reform of water charge. However, other agricultural practices including fertilizer application have also changed and will have contributed to yield increases. Based on the analysis of the data from the experimental station and the investigations in the typical areas, the irrigation water productivity in the Zhanghe Irrigation System was 0.65–0.82 kg/m^3 before and 1.18–1.50 kg/m^3 after the application of AWDI.

Another example is from the Juankou Irrigation District in the Yulin Prefecture, Hunan Province with an irrigated area of 2,100 hectares. Before 1989, the land was cultivated (with rice) in only seven months (April-October) and lay fallow in the other five months due to lack of irrigation water. Since 1990, water saving irrigation for rice has been adopted and the average gross irrigation quota for rice has been reduced by 180 mm. As a result, half of the agricultural land has been planted with vegetables in the winter and the farmers' average annual income has increased by about 27 percent.

AWDI was considered particularly suitable for areas with sandy soils, such as the alluvial plain of the Yellow River basin, where rates of evaporation and percolation are high and there is a low tendency for the soil to crack. But, later studies in Hubei and Jiangsu Provinces also showed positive results (Lu Baolin 1988). Mao Zhi (1996) reported recently that about 100,000 hectares are now under AWDI in the Guanxi Autonomous Region and Hunan Province.

Indian Studies

The Tamil Nadu Agricultural University has been carrying out studies on water management in the Periyar-Vaigai irrigation scheme. In the command area of a tank in this scheme, three types of water management were tested on farmers' fields. These were: (1) the conventional method of continuous submergence; (2) AWDI with irrigation to a depth of five centimeters one day after disappearance of ponded water; and (3) water supply in a four days 'on' and three days 'off' rotational schedule. Results obtained from two seasons are given in table 3.

The Indian Council of Agricultural Research (ICAR) has carried out a series of on-farm water management studies in major irrigation commands of the country during the last three decades. The methodology consisted of implementing a package of interventions, which included AWDI and selected technology trials in the entire command of one or two outlets of a minor or distributary canal and comparing the results with an adjoining outlet treated as control. The results pertaining to rice irrigation are presented in table 4. The table presents some interesting observations:

- In all the centers there was an increase in grain yield and concomitant decrease in irrigation water supply in the experimental fields, where the package of intervention was introduced compared to control fields where continuous submergence was practiced. However, the percentage increase in grain yield and the percentage decrease in irrigation water supply varied over a wide range. Also, the range of absolute values from center to center varied widely.

- A number of reasons may be responsible for these wide variations. In the case of grain yield, non-water factors such as rice variety, climate, type of soil, amount of fertilizer applied, and rice pests may affect the yield in addition to water factors. In the case of water saving, the rainfall and its pattern, type of soil and the place of measurement with respect to the field plot are important.

- A more general conclusion, which can be drawn from this research is the superiority of AWDI against continuous submergence in that it increases the grain yield by 20–87 percent and reduces the water supply by 10–77 percent.

TABLE 3.
Results of water management studies in Tamil Nadu.

Description	Conventional method		AWDI		Rotational water supply	
	Rabi[a] 95	Kharif[b] 95/96	Rabi 95	Kharif 95/96	Rabi 95	Kharif 95/96
Total water used (cm)	117.4	80.2	96.8	77.0	107.8	76.3
Water use efficiency (kg/m^3)	0.45	0.58	0.54	0.67	0.49	0.68
Yield (t/ha)	5.32	4.63	5.21	5.17	5.24	5.22
Percentage of water saved over conventional method	-	-	17.2	4.5	8.2	5.6

[a] Agricultural season from April to September. [b] Agricultural season from October to March.
Source: Tamil Nadu Agricultural University (1996).

Vector Control

Rice Cultivation and Vector-Borne Diseases

The key questions that have to be answered when water management measures are considered for vector- borne disease control in rice agro-ecosystems are: (1) What are the local vectors? (2) Where do they breed? (3) Are the breeding opportunities created in the irrigated area likely to contribute significantly to the overall vector abundance and disease transmission level? Vector ecology and disease transmission are dynamic and complex processes and it is sometimes difficult to draw general conclusions. This should be kept in mind when reading the examples from the different countries.

TABLE 4.

Results of on-farm water management studies by research centers of the Indian Council of Agricultural Research (ICAR).

ICAR center	Type of soil	Season	Rice varieties	Method of water application	Yield in AWDI fields (t/ha)	Yield in control fields (t/ha)	Water use in AWDI fields (cm)	Water use in control fields (cm)	Water saving of AWDI (%)	Increase in yield of AWDI (%)
Pusa, Bihar	-	Kharif	Rajashree (HYV)[a]	7 cm irrigation after 3 days dry	3.10	2.10	-	-	34	48
			Bakol (local)		2.40	1.80	-	-	34	33
Chiplima, Orissa	Loam to sandy loam	Kharif 1993-94	Lalat	7 cm irrigation after 3 days dry	3.41	2.95	37	72	49	16
Navasari, Gujarat	Deep clay	Summer 1993[b]	Hansuri	7 cm irrigation after 1 day dry	7.18	5.86	138	172	20	23
					6.61	6.01	120	169	29	10
Chalakudy, Kerala	Sandy loam	Rabi and summer	Chitini red	7 cm irrigation after 1–2 days dry	2.80	1.58	153	720	79	77
			Chitini		3.35	2.01	54	420	87	67
Bhavanisagar, Tamil Nadu	Sandy loam	Rabi	ADT-38	5 cm irrigation after 1 day dry	6.96	5.57	96	124	23	25

[a] High yielding variety. [b] In certain parts of India, irrigation is practiced in three seasons: kharif, rabi, and summer; see also footnotes for table 3.

Source: Batta et al. 1998.

In Sri Lanka, the principal vector of malaria is *Anopheles culicifacies*, which breeds in streambed pools but not in rice fields. Only *An. culicifacies* sibling species B is found in Sri Lanka (Abhayawardana et al. 1996). In India by contrast, this species is considered a rice-field breeder but not a vector. In India, malaria transmission is predominantly confined to the north of the country and the most important vectors are *An. culicifacies* sibling species A, *An. nigerrimus*, *An. fluviatilis*, *An. stephensi*, and *An. annularis* (Service 1993). All except *An. stephensi* breed in rice fields to a greater or lesser extent. In contrast to the culicine vectors of Japanese encephalitis (JE), however, few anopheline vectors of malaria utilize rice fields *per se* as their main breeding habitat in India. The most commonly encountered breeding sites of malaria vectors are actually canals and fallow fields rather than rice fields under cultivation. Sharma and Mehrotra (1986) concluded that in India, rice cultivation has a very weak or no relationship to malaria transmission. In Madagascar the main vector of malaria is *An. funestus* which almost exclusively breeds in rice fields (Laventure et al. 1996). In West Africa, the same vector is never found in rice fields. However, the main vector of malaria in most of sub Saharan Africa, *An. gambiae s.l*., has long been associated with rice cultivation (Surtees 1970; Lindsay et al. 1995). In Kenya, there was a 70-fold increase in the population of adult *An. gambiae* caught biting people on the Ahero irrigation scheme compared with an area of undisturbed settled agriculture (Surtees et al. 1970).

Most vectors prefer sun-exposed breeding habitats, and therefore, the numbers may decline when rice plants grow taller and the vegetation canopy closes. An example is *An. arabiensis*, one of the sibling species of the *An. gambiae* species complex, which breeds in the early stages of the rice crop. The opposite can occur with anopheline mosquitoes that prefer shade. For example, in California, rice fields with rapid early canopy development had greater populations of *An. freeborni* larvae than fields with more slowly developing vegetation canopies (Wood et al. 1991). In Africa, *An. gambiae* and *An. arabiensis* are often replaced by *An. funestus* when the canopy closes (Service 1989b).

Even when local disease vectors breed in rice fields, this does not necessarily lead to more human disease. When the malaria situation in Africa started receiving attention in the 1930s, it was already speculated that only the general raising of standards of living would lead to improvements in the malaria situation (Litsios 1996). This is exactly what is expected from irrigation development. Improved standards of living result in less contact with mosquitoes when people live in better houses and make more use of preventive measures. Also, better access to health care and anti-malarial drugs, and more willingness to take sanitary measures can play a role. In Tanzania, a village with rice irrigation had higher numbers of malaria vectors but less intense malaria transmission than a nearby savanna village (Ijumba 1997). The irrigated village was more affluent with better nutritional status of children and greater use of bed nets. Studies in different ecological zones in West Africa found high densities of malaria vectors in rice irrigated areas but the incidence of malaria was lower than outside the irrigated areas (Teuscher 1998). In contrast, in Burundi, there was a very localized high prevalence of malaria close to irrigated rice fields and flooded areas (Coosemans et al. 1984). The irrigation development lead to a stabilization of previously instable malaria. An irrigated rice area had a much higher prevalence of malaria than a cotton area 20-km away (Coosemans 1985). In Sri Lanka, the Mahaweli Development Project* caused a sharp increase in malaria incidence

*A large-scale development project in Sri Lanka. Approximately one million settlers moved to the irrigated rice lands developed under the Mahaweli Project.

(Goonasekere and Amerasinghe 1988). The introduction of irrigated rice production was also associated with the first ever-recorded outbreak of JE in Sri Lanka in 1985/86. These problems appear to have been caused by the increase in irrigated rice, an increase in pig farming, and the movement of settlers into the project area (Peiris et al. 1992). In Tamil Nadu, India, a poor correlation between the number of recorded cases of JE and the total area under rice cultivation was found. Still, the observed increase in JE since the 1960s was ascribed to an increase in rice cultivation, possibly as a result of multiple crops of rice being grown and a consequent increase in vector densities (Center for Research in Medical Entomology 1987).

Early rice cultivation in Asia was small-scale, relying on manual irrigation from reservoirs (tanks), with seasonal flooding and drying. Good management of scarce water supplies appears to have been responsible for maintaining vector populations at low levels (Self and De Datta 1988). In contrast, modern systems tend to be large, using large quantities of water diverted into water-scarce areas. In terms of food production, they may be very successful, but there are often consequences in terms of human disease, and these potential negative effects are often overlooked during feasibility studies and environmental impact assessments. Furthermore, many schemes are poorly designed and constructed and this can lead to a proliferation of mosquito and other vector-breeding sites. The improper elevation of canal beds, erosion from unlined canals, and seepage from poorly designed and constructed canals can all lead to the creation of stagnant and sunlit pools which are often ideal mosquito-breeding sites (Goonasekere and Amerasinghe 1988).

Indonesia

Several studies were done early twentieth century, in the Indonesian archipelago on ‘intermittent irrigation.’ These have been reviewed in Takken et al. (1990). A cycle of 9 days wet and 2 days dry in 15 hectares field trials in Bali reduced the density of the malaria vector *An. aconitus* by 75 percent. This research had a remarkable direct impact on decision making and led the local administration to make AWDI obligatory in Bali and Lombok despite some reduction in yield under AWDI.

Portugal

In the 1930s, South Portugal had a serious malaria problem related to submerged rice cultivation. Hill and Cambournac (1941) reported considerable success in controlling the anopheline vector of malaria *An. atroparvus* using a cycle of 10 days with water followed by 7 days without. Late stage larvae and pupae were reduced by up to 80 percent in the experimental plots compared with the control plots subject to continuous water supply. Average water use in AWDI fields over a three-year period was 301 m^3/ha/day, against 365 m^3/ha/day in flooded fields. AWDI also reduced weed and algae growth and improved grain yields with no effect on rice quality. In fact, as a result of a law passed in 1938, AWDI was deemed compulsory in Portugal if required by the Malaria Service (Russell et al. 1942).

East Africa

Grainger (1947) carried out experiments in western Kenya with AWDI on 13 plots of approximately 20 square meters each, separated by irrigation channels. One plot was subjected to continuous flooding, whilst the other 12 were irrigated with a variety of wet and dry cycles ranging from 3 days irrigated and 7 days dry to 5 days irrigated and 4 days dry. In the first year, larval control was unsuccessful as the fields failed to dry out before adult mosquitoes had emerged, illustrating the importance of soil drainage characteristics for the success of this method. In the second year, heavy rainfall actually increased larval numbers compared to the previous year. There was some evidence that AWDI, as practiced here, was effective against *An. funestus* and *An. coustani,* as populations of these species were much higher in the field under continuous irrigation, but not against *An. gambiae* and *An. pharoensis*.

In a study in experimental fields in the Mwea rice irrigation scheme in Kenya in 1998, higher numbers of *An. arabiensis* 1st instar larvae (see box 2) were found in AWDI fields than in continuously flooded fields, indicating that the AWDI water regime provided the most attractive environment for egg laying (Mutero et al. 2000). However, the ratio between the 4th and 1st instar larvae for AWDI fields was only 0.08, indicating very low survival rates. In contrast, the 4th / 1st instar ratio for the non-AWDI fields ranged between 0.27 and 0.68, suggesting much higher survival under flooded water management regimes. Rice yields and water use did not show statistically significant differences among fields with different water regimes in this study where active drainage was used in the AWDI fields.

Ijumba (1997) did experiments in the Lower Moshi irrigation scheme in Tanzania with different rice varieties and different water management methods. Active drainage was practiced and fields were left to dry out for three days before being flooded again for four days. AWDI resulted in increased mosquito production compared with permanent flooding. It was concluded that the small pools that were created by drying out the fields remained highly productive for the malaria vector. The results showed no evidence of significant association between different varieties of rice and mosquito productivity.

The studies in East Africa clearly show the importance of land preparation. If land leveling is not done properly, numerous small puddles will be left behind and this could even increase the egg laying potential if AWDI is practiced.

India

In the early 1940s, a three-year study was carried out by Russell et al. (1942) in Pattukottai, Tamil Nadu, where climatic conditions were generally favorable for rapid drying out of fields, except during the northeast monsoon period in November. In this area, one rice crop was grown between mid-July and mid-January. The most common malaria vector mosquito was *An. culicifacies*, which was found during the period when the rice fields were wet fallow, prior to transplantation of the seedlings, with a peak in population density in late August and early September. Breeding continued until the rice plants had reached a height of approximately 30 centimeters, after which the population of this species declined, to be replaced by two non-vector species, *An. pallidus* and *An. hyrcanus*. In this experiment, different wet and dry cycles in experimental fields were compared against fields that were continuously flooded to a depth of 10 centimeters, which was the average depth used by local farmers. It was found that one day was not sufficient to drain surface water in any of the plots, and four days was the maximum period of drying before cracks and clods formed in the soil. A system of five wet and two dry days per week practiced from the time irrigation water was made available in mid-June until the rice was in flower was effective against vector breeding and had no ill effect on the crop. AWDI successfully controlled mosquito populations except during the monsoon period, when even four days were not sufficient to dry out the fields. However, at that time of year the rice plants were usually more than 30 centimeters in height and so populations of the vector *An. culicifacies* were naturally low. Russell et al. 1942 emphasized the importance of careful control of water availability in order to ensure the success of the method. As was common in the first half of the twentieth century, there was a lot of interaction between engineers and other people involved in malaria control.

BOX 2.
The basic information on the entomology and epidemiology of Malaria and Japanese encephalitis.

Malaria

Malaria is the main health problem in many countries with an estimated 300–500 million clinical cases each year and two million deaths. Most affected is sub-Saharan Africa, but malaria is also a serious problem in several countries in Latin America, South Asia and South East Asia. The disease is caused by protozoan parasites of the genus *Plasmodium*, of which four species affect humans. *Plasmodium falciparum* is the most dangerous species and can result in high mortality amongst nonimmune individuals. It is the most common species in Africa. In Asia, *P. vivax* is the most common species, which while causing only low mortality may be responsible for a high degree of morbidity. The malaria parasite is spread from human to human by some, but not all, species of mosquitoes of the genus *Anopheles*, many of which breed in rice fields and other irrigation structures. The vector mosquitoes have restricted breeding sites and often feed at specific times of the night. Transmission also depends on human exposure and the preventive measures that are used such as mosquito nets and repellents. Mosquitoes frequently fly from breeding sites to human settlements in order to feed.

Japanese encephalitis

Japanese encephalitis (JE) is one of a large group of viral diseases that are transmitted through insects. JE is the most important mosquito-borne viral encephalitis, with up to 50,000 cases per year, of which the majority are children under the age of 15 years (World Health Organization 1994). The disease occurs in countries in East Asia, South East Asia, and South Asia. The JE virus is normally found in wading birds and is transferred by the bite of mosquitoes that breed in rice fields to other animals, especially pigs. Pigs are considered to be amplifying hosts, as they greatly increase the quantity of the virus. When the populations of animals that harbor the virus and mosquito vectors are sufficiently high, the infection can spill over into the human population, resulting in seasonal epidemics, often following periods of heavy rainfall or the start of the irrigation for rice. JE is a man-made problem, prevailing under the combination of paddy rice production and livestock breeding (Mogi 1984). JE is a much less frequent disease than malaria, but mortality often approaches 25 percent, with up to 50 percent of the survivors experiencing permanent neurologic damage (Vaughn and Hoke 1992). The majority of infections, however, do not result in any symptom and it has been estimated that there may be as many as 300 infections without symptoms for every clinical case of encephalitis. The vectors of JE in South and East Asia– *Culex tritaeniorhynchus*, *Cx*. *vishnui*, *Cx. gelidus*, and *Cx. fuscocephala* all use rice fields as their main breeding habitat. *Cx. tritaeniorhynchus* is the most studied species of the JE vectors. It predominantly feeds on animals, and bites mainly outdoors, at night (Self et al. 1973).

Mosquito biology

A mosquito passes through four stages in its life cycle. The stages are the egg, larva, pupa, and adult. Eggs, larvae, and pupae must have standing water to develop. There are four larval growth stages, called “larval instars.” All larval stages resemble each other, except that each stage is larger than the preceding one. The first stage hatches from the egg and the fourth stage becomes the pupa.

Singh (1948) commented on the work of Russell and stated that despite its wide use in Bulgaria, Russia, and Portugal, AWDI could probably not be introduced in India because of the need to adapt the irrigation infrastructure and because of reluctance of farmers to change their methods of cultivation. However, he also advised that flooded rice cultivation 'should be prohibited within a radius of at least one mile from the outskirts of towns and cities.'

More recent evaluations of AWDI to control mosquitoes that breed in rice fields in India have been carried out during the 1980s and 1990s near Madurai, in Tamil Nadu, by the Center for Research in Medical Entomology in collaboration with the Tamil Nadu Agricultural University (Reuben and Jayaraj 1991; Center for Research in Medical Entomology 1990). In this area, surface water has been fully exploited, and the limit of groundwater potential is rapidly being reached; any further expansion must therefore rely on improved water management practices. AWDI was practiced on a pilot scale in part of the Periyar-Vaigai system, which had recently been modified and upgraded with the assistance of the World Bank. On a pilot scheme consisting of 100 hectares, 40 hectares were irrigated under local farmers' practices, ie., continuous flooding when water was available, the remaining 60 hectares were subject to a water management regime, whereby the fields were flooded, allowed to dry out and then immediately re-irrigated. In the continuously irrigated fields, there were high levels of culicines for at least seven weeks after transplanting, due to continuous submersion and asynchronous planting. Under AWDI, vector breeding was reduced to a period of three weeks post transplanting, and water savings of 15–20 percent were made. There was no clear cut reduction in anopheline densities as the dominant species was *An. subpictus*, which breeds in rice fields during the early stages of rice cultivation, before the fields can be dried out (Center for Research in Medical Entomology 1991). In years when water was scarce, conditions forced the farmers to adopt AWDI practices. Farmers were appreciative of the benefits of this system of irrigation, and would even employ laborers to operate the sluice gates, however, the authors reported that the farmers doubted their own ability to regulate the equitable distribution of water between farms, especially when water is scarce, and a neutral external agency acting in a supervisory capacity was preferred. A further problem noted was the high vector population immediately after transplantation, when water levels must be maintained to allow for establishment of seedlings.

Rajendran et al. (1995) conducted another study near Madurai on heavy clay soils. A total of 16.2 hectares was kept under flooded irrigation and 22.3 hectares under AWDI. In the conventionally-irrigated fields, field-to-field drainage was practiced and a water depth of 5–15 centimeters was maintained throughout the growing cycle, except for a period of 10–14 days just prior to harvesting. In the AWDI fields, there was no field-to-field irrigation and transplantation was synchronous. A water depth of 2.5 centimeters was maintained for the first 10–14 days after transplantation, after which the fields were allowed to dry out naturally, before being re-irrigated to a depth of 5 centimeters as soon as all standing water had disappeared. The dominant mosquito species sampled were *Cx. tritaeniorhynchus*, *Cx. vishnui*, and *An. subpictus*. In 1990, water was scarce due to drought and was only available for irrigation of either block for three days per week. As a result of the similarities of irrigation management on the two plots, there were no significant differences between them in terms of larval and pupal densities and grain yields. In 1991, ample water was available for irrigation and a significant difference in the numbers of mosquito pupae collected was observed in all weeks, except the first, when all fields in both blocks were flooded. In addition, there was a significantly higher grain yield in AWDI fields (5.66 t/ha compared with 5.42 t/ha estimated from random samples of one square meter plots). It was also reported that using this method of irrigation, the fields never dried out completely and numerous small puddles remained. Larvae of culicine mosquitoes were often observed crawling across the soil surface to reach these remaining pools of water, but anopheline larvae did not. Populations of Notonectidae, potential mosquito larval predators, were reduced in the fields under AWDI, but populations of other predators (Odonata and Dytiscidae) were not affected, and the authors ascribed the marked reduction in larval and pupal mosquito abundance in AWDI irrigated fields to enhanced predation as a result of larval Odonata becoming concentrated in the pools of water formed at the end of the drying period.

Due to the problems of adult mosquito emergence during the 10–15 days immediately following seedling transplantation, during which rice plants must be submerged, two recent trials with neem 'cake' and commercially available extracts have been carried out. Neem is obtained from the tree *Azadirachta indica* and is widely used in Asia as a fertilizer, however, it also contains a number of substances with insecticidal properties. Rao et al. (1992) conducted the first trial, primarily against JE vectors at Madurai. In this trial, neem cake powder was first tested in the laboratory against fourth instar larvae of *Cx. tritaeniorhynchus* in order to assess its quality. In October 1989, a 4,500 square meters rice field was subdivided into nine plots of 500 square meters and treated with 500-kilogram neem cake powder per plot. In a second trial in 1990, neem cake coated onto urea was also tested in conjunction with AWDI. Pupal abundance, but not larval abundance, was found to be greatly reduced in the fields under AWDI. Neem cake coated urea combined with AWDI also reduced larval populations and the amount of neem could be reduced to half (312 kg/ha) compared with the amount when used alone. However, this still represented four times the normal recommended agricultural dose. Neem cake powder and neem-coated urea did not appear to affect anopheline populations, and this was thought to be due to the substances sinking to the bottom of the water, where they would not come into prolonged contact with the surface feeding anopheline larvae.

In a later trial (Rao et al. 1995), a commercially available neem-rich product was coated onto urea and tested to determine if this allowed for greater certainty over quality and ease of use for farmers. The product was applied to plots using a knapsack sprayer immediately after transplanting seedlings of a short-term rice variety. The abundance of culicines in control plots was high for four weeks after transplanting, then negligible. Pupal peaks occurred in the second and fourth weeks. All treatments reduced pupal numbers, but the greatest reductions were observed in plots treated with neem-coated urea at a dose of 0.09 kg active ingredient per hectares. As in the previous trial, the treatments had no effect on larval anophelines (of which 99 percent were *An. subpictus*) although there was a slight but significant reduction in pupal abundance. The use of AWDI also led to increases in grain yield. Combinations of neem and AWDI reduced populations of four groups of insect predators, except when neem was applied in the cool season, indicating that the timing of application may also be important.

China

The most important vector of malaria in China is *An. sinensis*, which mainly breeds in rice fields (Service 1989b). Increase in populations of this vector coincides with irrigation of the rice fields, reaching a peak once a year around August–September. In areas that cultivate two crops of rice per year, a double peak in mosquito vector population densities is experienced (Bhuiyan and Sheppard 1987). *An. sinensis* populations seem to have increased with expanding areas of rice cultivation (Lu Baolin 1984). However, introduction of AWDI in the 1970s, coincided with a dramatic reduction in malaria morbidity. The method is referred to as 'wet irrigation' and involves a period of continuous submersion for 10–15 days post transplanting, after which the fields are allowed to dry naturally before being re-irrigated immediately when all surface water has disappeared. This leads to 21–26 irrigation events during the 100-day growing period of the rice plants, with standing water disappearing within 1–2 days because of percolation and evaporation. This 'wet irrigation' variety of AWDI has been extensively applied since 1978 in Henan Province to control *An. sinensis* and the JE vector *Cx. tritaeniorhynchus* (Lu Baolin 1988). AWDI led to a reduction in the size of the immature population of *An. sinensis* by 84–86 percent and *Cx. tritaeniorhynchus* by 81–91 percent. There was a reduction in adult density of both species of more than 50 percent. AWDI yielded an average of 7.2 tons of rice per hectare, compared with 6.4 t/ha under conventional irrigation. High water savings were reported. The success of the project led to its acceptance by most members of the local communes and by the mid 1980s 35,000 hectares were under AWDI (Lu Baolin 1988).

Self and De Datta (1988) presented the results of a case study on rice cultivation and malaria carried out in Shangdong Province, China. In this area, *P. vivax* malaria, transmitted by *An. sinensis*, was the third leading cause of morbidity. Increased rice production was considered the main reason for continued malaria transmission despite control efforts. In 1958, the switch from dry land farming to irrigated rice cultivation began, with AWDI commencing in 1977 in order to control *An. sinensis*. In this trial, yields increased remarkably but the dry period was felt to be too short to kill all larvae and the effect on the vector population was not significant. Grading and filling of other depressions, along with other environmental modifications carried out in the villages around the irrigation schemes appear to have been successful in reducing malaria.

Japan

Several studies in Japan have shown reductions in mosquito populations under AWDI (Mogi 1988). AWDI is a standard practice since the 1960s but only from about one month after transplanting. Studies of AWDI for vector control in Japan have focused on *Cx. tritaeniorhynchus*, the main vector of JE (Mogi 1993). Predators of mosquito larvae are known to represent an important cause of mortality in rice fields, so effects on these non-target organisms may have consequences for mosquito population dynamics. A study was carried out at Kinryu, Saga City, western Japan. In this area, rice seedlings are normally transplanted in early July following a crop of winter barley. Two fields were selected for the experiment: one of 0.22 hectares and one of 0.11 hectares, with a comparison field of 0.06 hectares. All fields were treated with carbamates by their owners to control rice pests in keeping with usual farming practices. The study fields were subject to repeated flooding and drying, whilst the control field never completely dried out. The soil surface was observed to crack after 3 continuous days of no surface water. In the first experimental field, mosquito abundance remained low after drying, but in the second field, *Cx tritaeniorhynchus* and *An. sinensis* populations recovered to temporary high levels. There was also a decline in the numbers of *Cx. tritaeniorhynchus* in the control field, but the author could provide no explanation for this. There was no evidence of any effects from the agricultural insecticides on the mosquito populations. The predator populations also decreased with drying and remained low during AWDI, with fish populations in particular suffering high mortality. The general effect of this water management regime was to reduce the diversity of the aquatic communities and increase relative mosquito dominance as mosquito populations recover more quickly than predator populations. The author suggested that if AWDI is not practiced very carefully, it might favor mosquito reproduction in re-irrigated fields in the presence of a reduced predation pressure.

A comprehensive study of the population density of *Cx. tritaeniorhynchus* in Japan over a period of forty years (Mogi 1987) emphasized the complexity of the epidemiology of JE. Mosquito populations decreased by 90–99 percent in the late 1960s as a result of increased use of insecticides that were effective against the vector, but now appear to have recovered following the acquisition of insecticide resistance. There has been a resurgence in the infection rate of pigs, but the number of human cases remains below 0.01 cases per 100,000 population (compared with more than 10 per 100,000 in the 1960s). There appears to have been a reduction in man-vector contact as a result of socioeconomic changes. More inhabitants have television sets and air conditioning systems that have led to people staying indoors more during the evening. The area under paddy cultivation and the planting date showed no relationship with vector abundance, suggesting that this species of vector is not limited by breeding site availability. The use of AWDI in rice cultivation has also increased since the 1960s but this has not affected vector abundance. The vector is either utilizing an alternative-breeding site, or its population is limited by the availability of hosts, not breeding sites. The author concluded that large-scale environmental and socioeconomic changes in conjunction with a vaccination program, have reduced the incidence of JE.

Care must be taken to conclusively prove a causal link between control interventions and changes in disease incidence and prevalence. In addition to the complicated ecology of JE virus transmission, the high ratio of inapparent to apparent infections makes it very difficult to accurately monitor the effects of any intervention against JE on incidence and prevalence in the human population. The incidence of disease *per se* is not a sufficiently accurate indicator of the level, duration or periodicity of transmission of the virus. Other indicators that could potentially be used to investigate the effects of an intervention include the detection of virus antigens in the mosquitoes and rates of seroconversion in human cohorts. However, this second method requires communities to cooperate for more than one or two years, which is often difficult to achieve (Amerasinghe 1993). In addition, serological tests may not distinguish between JE and dengue or other similar viruses (Vaughn and Hoke 1992).

Other Control Methods

AWDI is a vector control method that should be used together with other vector- and disease-control methods. In the United States, control of adult mosquitoes emerging from rice fields is predominantly undertaken using aerial application of insecticides (Lacey and Lacey 1990). At ground level, ultra-low-volume (ULV) generators and thermal foggers are used. In Korea, ULV fenitrothion delivered by aircraft reduced adult mosquito populations by 80 percent, but the effect only persisted for four days (Self et al. 1973). Malaria vectors are usually controlled by spraying residual insecticides in houses. This is to kill the adult mosquitoes, which often rest on the interior surfaces of houses and other structures. This method is ineffective against vectors of JE which tend to bite and rest outdoors. Control of JE vectors with insecticides is generally only used to suppress outbreaks or to target epidemic-prone villages at the start of the rainy season. Larvicidal control of rice field breeding mosquitoes is rarely practiced currently, due to the huge areas that need to be sprayed, the short lifespan of insecticidal treatments, and the problem of increasing resistance, especially to the organophosphorus and carbamate insecticides (Wada 1988). Recolonization after insecticide application may be very quick especially when natural predators have been eliminated. It may also be possible to limit man-vector contact by positioning houses away from rice fields and piggeries, but this is usually impractical except when new agricultural development projects are initiated. Light traps placed in animal sheds have been suggested to control the vectors of JE (Mogi 1984). Personal protection measures such as remaining indoors after dusk, screening living quarters, using bed nets, protective clothing, and repellents are all useful tools to reduce the number of mosquito bites received, but they are often impractical or too expensive for rural populations in developing countries. While there is no vaccine available against malaria, a first vaccine to prevent humans from JE was licensed in Japan in 1954, and has been made commercially available since 1962. During the period up to the early 1990s, approximately 500 million doses of JE vaccine have been administered in China, Taiwan, Korea, and Japan with apparent success (Wada 1988; Vaughn and Hoke 1992). A vaccine for pigs has been available in Japan since 1972, but due to the high turnover of pig populations, vaccination strategies are problematic (Umenai et al. 1985).

Other Aspects of AWDI

Agrochemical Use

Reducing the use of chemical pesticides as part of integrated pest management (IPM) is now considered a key component of sustainable agriculture. Changes in irrigation water management should therefore not increase the need for pesticide application. Keeping rice fields flooded is considered a good method to control weeds. A main concern with AWDI is therefore that the need for chemical herbicides would increase. Farmers often practice continuous submergence of rice fields to reduce weed problems. However, Tabbal et al. (1992) found in Central Luzon, Philippines, that in situations where weed pressure was high, continuous submergence up to the panicle initiation stage followed by continuous saturation required 35 percent less water input than continuous flooding, without any yield reduction or increase in weed infestation.

Insect pests of rice are generally reduced under AWDI (Mao Zhi 1996). In Colombia, a system of weekly flushing against permanent flooding in rice fields resulted in fewer eggs, mines and pupae of the rice leafminer (Pantoja et al. 1993). In experiments in Louisiana, drying of rice fields was effective in controlling the rice water weevil, the most economically important insect pest of rice in the U.S. (Quisenberry et al. 1992). Also, the brown plant hopper (*Nilaparvata lugens*) is known to be adversely affected by AWDI because eggs laid at the base of the plant, near the waterline dry out and die. This is one possible reason for increased yield under AWDI. However, in the study of Russell et al. (1942) in India, the rice 'blast' fungus *Piricularia oryzae* affected the rice crops under AWDI more than those which were continuously irrigated, and this rice disease was known to be associated with drought years. In Tamil Nadu, increased rodent damage to rice plants was reported (Tamil Nadu Agricultural University, unpublished data).

Under AWDI, the fertilizer losses with percolation and seepage water are reduced (Mao Zhi 1996). AWDI leads to a lower groundwater table and a higher soil oxygen content, which is very favorable for the transformation and assimilation of organic fertilizer. In the Zanghe Irrigation System, Hubei Province, China, nitrogen uptake efficiency was greatly increased under AWDI (Li Yuanhua, personal communication). Nutrient status and physicochemical dynamics of flooded soils are complex and the possible effect on nitrogen uptake efficiency, the environment, and weed population dynamics stemming from AWDI should be further determined. Water use efficiency and nutrient use efficiency have to be evaluated together to identify the optimum combination of water and agronomic management.

Institutional Aspects

The challenge of using AWDI or any other means of environmental control is to determine if such modified cultural practices can be introduced and accepted by farmers on a large scale, whilst preserving crop yields, and maintaining the work load at previous levels (Gratz 1988). Bos (1986) identifies five criteria for the effective use of environmental management for vector control. The measures used must be:

- known to be effective against the target vector
- socially acceptable
- cost-effective compared with other feasible methods
- economically sustainable by the local community
- compatible with local agricultural practices

In addition to the above general requirements for environmental management, a number of requirements specific to AWDI have also been identified (Amerasinghe 1987) and these include a well designed irrigation and drainage system that allows for rapid flooding and drying and which is efficient enough to allow for synchronous irrigation and drainage of all fields within the system.

Often concerns are expressed about the possibility of implementing AWDI because of farmers' reluctance. However, in China, it has been possible to implement AWDI on a large scale mainly because volumetric charges for water provided an important incentive for farmers to use less water (Li Yuanhua, personal communication). There is anecdotal information that the method is adopted more and more in India for opportunistic reasons, because of scarcity of water. In Sri Lanka, on several occasions farmers used AWDI because of water scarcity and this led to higher yields instead of the expected lower yields (IWMI, unpublished data).

Mogi (1988) has stated that AWDI can only be successful for vector control if simultaneously practiced for all rice fields over a large area, during the entire cropping season. This again could be a problem in areas, where farmers practice asynchronous cultivation and where there is no institutional mechanism to implement and sustain changes.

AWDI techniques require more control over the amount and timing of water application than traditional practices. Further research is needed to determine how to implement effective soil saturation or very thin standing water in irrigation systems where the plot-to-plot method of water distribution is dominant and whether the sustainable adoption of AWDI regimes would require a greater density of field irrigation channels. Additional infrastructure in the irrigation system (such as control structures) may also be needed for AWDI implementation.

East Africa has no long tradition of irrigated rice cultivation and new methods might be easier to implement than in Asia.

Global Climate Change

Flooded soils such as those for irrigated rice produce methane, a greenhouse gas that plays an important role in global climate change

(Lindau et al. 1993). Research is being done by the International Rice Research Institute (IRRI) and national rice research institutes in China, India, Indonesia, the Philippines, and Thailand to look at methane emission levels in irrigated rice fields. When rice fields are dried, oxygen becomes available in the root zone and this reduces methane emission. AWDI is therefore a potential method to reduce methane emissions (Nugroho et al. 1994). However, the discussion on the role of rice cultivation in global climate change is still in its early stage.

Subjects for Further Studies

The following are some specific points that have to be addressed in further studies:

- Most studies on the effects of AWDI were done in small experimental fields. There is a need for more studies in farmer-managed fields. Currently, IWMI is implementing such studies in Tamil Nadu with the Tamil Nadu Agricultural University and in the Zhanghe Irrigation System in Hubei Province, China with IRRI and the Wuhan University of Hydraulic and Electric Engineering.

- Studies need to distinguish active versus passive drainage and scheduled versus on-demand flooding.

- Studies of AWDI need to be extended to consider the effects on disease prevalence and incidence, rather than just mosquito-vector populations. Most studies so far have relied on collection of mosquito larvae from rice fields under different water management. This can adequately describe the suitability of the habitat for the vector. However, larval abundance might not be linearly related to abundance of adult mosquitoes and adult mosquito abundance might not translate into human disease. It is therefore essential that future studies take the human disease incidence and prevalence as outcome measures of water management interventions, with the sampling of larvae and adult mosquitoes as support to prove the causal link between water management and human disease. But disease is multifactorial and may be reduced by a range of measures. For example, self-protection may increase when the wealth of the community increases.

- The relative importance of other sites, outside the fields themselves, such as irrigation and drainage canals and seepage areas for mosquito vector breeding needs to be determined. Many species of mosquito will breed in canals, hydraulic structures, storage reservoirs, and seepage areas, and controlling water regimes in rice fields alone, without adequate control of other breeding sites is likely to be of limited use (Bhuiyan and Sheppard 1987).

- Even under AWDI, rice crops must be maintained under continuous submergence during the 10–15 days after transplantation of seedlings. The vector production during this period may be at the peak because the irrigated area is greatest, and the most stable, and rice plants are short and sparse (Mogi 1984). The use of neem products and other insecticides and fertilizers in conjunction with AWDI has to be further evaluated.

- Effects of AWDI on other agricultural parameters, including fertilizer uptake and control of weeds and other pathogens require more detailed investigation.

- The role of predators in regulating mosquito populations in rice fields under different water management practices requires further investigation. Draining rice fields can affect insect predators of mosquito larvae and the remaining pools can be highly productive for mosquito larvae. But in Tamil Nadu, predation was enhanced by the concentration of predators with larvae in small residual pools.

- In areas or countries where flooded rice is grown, it may be interesting to compare the economics of flooded and non-flooded rice production, considering whether and how residual waters are returned to the hydrologic systems. For example, flooded rice culture in the lower delta region of Egypt consumes considerably more water than crop evapotranspiration, due to non-recoverable freshwater spills that are lost to the Mediterranean. In that setting, the potential water savings of non-flooded rice production may offset the expected lower yields. We need information on all input requirements and outputs to be able to compare the overall profitability and impact of the traditional versus the new system of water management. This will also have to be analyzed in the context of further scenarios of increasing labor cost for water management, weed management, insect and rodent pest control, and agrochemical requirements. The human health costs and benefits should also be taken into account in such economic analyses, including the health costs of disease transmission, reduced expenditure on other methods of vector control and the health benefits of increased wealth.

- There seems to be a potential to use AWDI as part of an integrated pest management (IPM) strategy in irrigated rice cultivation. This option should be explored in further studies.

- Studies on AWDI should include the institutional aspects. Farmer cooperation is essential for the effective use of AWDI, and identification of methods to foster cooperation and ensure correct water management practices is desirable. An institutional framework or support system for farmers is needed for the implementation of new management procedures. At the moment, very little information is available on what farmers perceive as restricting factors in implementing AWDI and this should be a key issue in future research.

- Water savings have to be estimated at the river basin level. If only on-farm water savings are considered, a distorted picture will be obtained because downstream farmers often rely on the surplus flows resulting from upstream percolation and runoff. Water that is "lost" from such rice fields can be the source of water for other rice fields. The potential water savings of AWDI at river basin level is now being addressed in the ongoing IWMI/IRRI study in Hubei, China.

- AWDI may affect the availability of water for domestic use if this water is drawn from allow aquifers recharged by seepage and percolation losses in irrigation canals and rice fields. Investigations into changes in groundwater levels and availability of water for domestic use should therefore be included in future research.

- AWDI has not been very successful in sub-Saharan Africa, where the need to control malaria is the greatest. Problems in trials have included insufficient drainage and poor leveling of fields. To fully appreciate the potential of AWDI for vector control in the (East) African context, properly designed trials should be undertaken, followed by studies in farmer's fields.

Conclusions

Table 5 summarizes some of the key vector studies that have been done on AWDI. Experiments and field testing of the AWDI method of cultivating rice from different parts of the globe have demonstrated the utility of AWDI for water saving in rice irrigated agriculture. Almost all the experiments indicate that water productivity increases and that land productivity (yield per unit of land) does not materially differ from continuous flooded irrigation. However, the extent to which these gains can be achieved differ over a wide range. These are mainly due to the method by which these field experiments were conducted, in addition to variables that are critical but that cannot be influenced such as the rainfall pattern and the soil conditions. Also, the experiments and field testing have demonstrated the infrastructural requirements, improved skills and management efforts in effecting water control to achieve the maximum benefits in terms of water saving and increased water productivity. A serious limitation of basically all studies done so far is that water savings have only been documented at field level, not at irrigation system or river basin level.

Studies of AWDI for both agricultural and entomological purposes have used either active or passive drainage. Active drainage has the advantage of allowing precise control of the water depth and it flushes mosquito larvae from the field. The disadvantages include low water saving, large labor input, loss of predators, and more complicated water management. In a system with irregular water supply it is very unlikely that farmers will actively drain their fields. Active drainage should therefore only be considered an experimental tool. In passive drainage, standing water is allowed to disappear through evapotranspiration, percolation, and seepage from the field. Larvae are killed by stranding on wet mud, predators are conserved, labor is minimized and there are large water savings, but pools left behind in the fields may increase egg laying.

Scheduled flooding introduces irrigation water into fields at fixed intervals, irrespective of the level of standing water or degree of dryness. It has the advantage of simplifying water supply predictions but the disadvantage of not responding to field conditions. It probably does not correspond to farmer's preferences. An alternative would be to re-flood when the water has percolated to some standard level of dryness as shown in the studies in South India . This may appeal to the farmers because they remain more in control than under a scheduled system. Rough calculations in Kenya suggested that natural drying would take 7–14 days, typically 10 days but dependent on flooding depth. But this will vary with soil type and temperature. Larvae take around 10 days to finalize their development and therefore a dry period is required at a shorter interval than this. The depth of flooding will increase with the height of rice following normal practices so that the frequency of re-flooding would decrease with time.

AWDI is an effective means for vector control in areas where the principal vectors of malaria or JE have rice fields as their main breeding sites and where rice fields are likely to contribute significantly to the overall abundance of adult mosquitoes. It seems most suitable for areas with unstable malaria transmission and extensive areas

TABLE 5.
Summary of studies on AWDI in which the effect on mosquito populations was quantified.

Study area	Year	Vector	Water supply	Drainage	Change in mosquito larvae* (%)	Change in water use* (%)	Change in yield* (%)	Reference
Bali, Indonesia	1936	*An. aconitus*	9 days wet, 2 days dry	Active	–75		– 8	Takken et al. 1990
Portugal	1936–39	*An. atroparvus* 7 days dry	10 days wet,	Active	–80	–18	+6 to +8	Hill and Cambournac 1941
Henan, China	1978–79	*An. sinensis and Cx. tritaeniorrhynchus*	5 day irrigation interval	Passive	–81 to –91	–53 to –67	+13	Lu Baolin 1988
Tamil Nadu, India	1990–91	*Cx. tritaeniorrhynchus*	3–5 day irrigation interval	Passive	–75 to –88		0 to +4	Rajendran et al. 1995
Mwea, Kenya	1998–99	*An. arabiensis*	3 days wet, 4^{th} instar larvae	Active 4 days dry	–9 to –48	–1 to +21	–2 to –9	Mutero et al. 2000
Lower Moshi, Tanzania	1995	*An. Arabiensis*	4 days wet, 3 days dry	Active	+11		–8	Ijumba 1997

* Compared with continuously submerged fields.

of irrigated rice cultivation, as is the case in many parts of Asia and in parts of East Africa. In hyperendemic areas such as West Africa, rice fields are often just one of many possible breeding sites and the control of mosquito breeding in rice fields may not have any effect on the level of malaria transmission and the overall incidence of the disease. Larval control in general might not be an option in areas where breeding places of the vector are diffuse and various such as for *An. dirus* in South East Asia and *An. gambiae* in Africa. In East Africa, there are larger schemes (> 10,000 hectares) with a more uniform environment than in West Africa and there it could be feasible to implement AWDI. Especially in Africa, multiple interventions are always needed at the same time in order to achieve effective malaria control.

AWDI is also a suitable method to reduce insect pests of rice, but might have adverse effects on weed management. AWDI, like all other environmental management measures must be selected and field-tested for local conditions. The important factors are farmer acceptance and compliance. Soils and climate should permit sufficient drainage and drying to prevent mosquito breeding yet allow normal plant growth.

Until recently, the idea of AWDI was not widely accepted by the irrigation community. The objections did not relate to agricultural yields, but to the complexity of the management. To conserve water, AWDI is now becoming a standard management practice in certain irrigation systems in India. The real success story is from China where AWDI is now widely accepted and implemented. Mao Zhi (1996) concluded that in Southern China, AWDI for rice should be more widely used because of its potential for saving water, increasing rice yield, and improving the water and soil environment. Results from other countries are sometimes inconsistent. More analysis is needed on the reasons why AWDI was more successful in China than elsewhere and whether water savings at the field level also resulted in water savings at the river basin level.

We conclude that in certain areas and under the right conditions AWDI is a promising method in irrigated rice cultivation with dual benefits of water saving and human disease control. However, because of the wide range of methods applied in the studies reviewed in this paper, it is difficult to draw general conclusions about the institutional and economic feasibility of implementing AWDI as a water saving and vector-control measure. It is important that comparative studies are done in different environments with the use of a common methodology. Further research would serve the dual purpose of studying AWDI as a possible method to reduce disease-vector abundance thereby decreasing the disease incidence among poor farmers, and as a way to conserve water under conditions of water scarcity while maintaining, or increasing, crop yields. The increased productivity of water, not the mosquito control, is likely to be the critical factor that will make farmers and irrigation department officials adopt AWDI in water-scarce areas.

Glossary

The glossary provides simple rather than precise scientific definitions to assist irrigation engineers to understand entomological terms and biomedical professionals to comprehend water management terms.

Alternate wet/dry irrigation (AWDI): The AWDI method of cultivating rice implies that rice fields are not kept continuously submerged but are intermittently dried during the rice growing stage. There is no uniform definition of AWDI and consequently there is an inconsistency in terminology. The term AWDI has been adopted in preference to intermittent irrigation, which could also apply to irrigation practices that deliver water intermittently without necessarily creating dry conditions. Commonly used terminology for AWDI includes 'water saving irrigation,' 'wet irrigation,' 'intermittent submerged irrigation,' and 'non-flooded rice irrigation.' In this report we refer to all these methods as AWDI.

Anopheles (An.): A genus of mosquitoes, some of which transmit malaria.

Culex (Cx.): A genus of mosquitoes, some of which transmit Japanese encephalitis.

Encephalitis: Inflammation of the brain. Victims may die or experience permanent brain damage.

Environmental management for vector control: The planning, implementation and monitoring of deliberate changes of environmental factors, with the view to preventing the propagation of vectors and reducing human-vector-pathogen contact.

Evapotranspiration (ET): Moisture loss to the atmosphere from plants by transpiration and from soil and surface water by evaporation.

Genus: A group of species with some similarities (a unit of classification of organisms).

Irrigation application efficiency: The ratio of water used by the crop to water received at the field inlet.

Panicle: The terminal shoot of a rice plant that produces grain.

Percolation: The downward movement of excess water through the soil.

Pupa: The non-feeding stage in an insect's development between larva and adult.

Sibling species: True mosquito species, which do not interbreed but are difficult to separate based on morphological evidence alone (see also species complex).

Soil moisture: Water contained in the soil, expressed as a percentage of weight of water per unit weight of dry soil or the percentage of volume of water per unit volume of soil.

Soil texture: The relative proportions of sand, silt, and clay particles in a soil.

Species complex: A mosquito species complex consists of a number of sibling species with almost identical morphological features but with differences in certain aspects of their biology, behavior and distribution. In most cases the distinction will have to be made using molecular biology techniques or studying the chromosome pattern (see also sibling species).

Tillering stage: The growth stage of the rice plant that extends from the appearance of the first tiller (vegetative branch of the rice plant) until the maximum tiller number is reached.

Vector: In this paper, a vector is a mosquito that can transmit the malaria parasite or Japanese encephalitis virus when it feeds on blood. Many species of mosquitoes are non-vectors because the parasite or virus fails to develop.

Water use efficiency index: Crop yield (dry matter of the crop produced) per unit of water supplied. This is a measure of water conservation.

Water productivity: Crop yield (dry matter of the crop produced) per unit of water consumed.

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